The efficiency of "viscous interaction" between the solar wind and the magnetosphere during intense northward IMF events

Bruce T. Tsurutani
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

W. D. Gonzalez
Instituto de Pesquisas Espaciais, Sao Jose Dos Campos, Sao Paulo, Brazil

Abstract. We examined 11 cases when the interplanetary magnetic field (IMF) was intensely northward (> 10 nT) for long durations of time (> 3 hours), to quantitatively determine an upper limit on the efficiency of solar wind energy injection into the magnetosphere. We have specifically selected these large B_N events to minimize the effects of magnetic reconnection. Many of these cases occurred during intervals of high-speed streams associated with coronal mass ejections when viscous interaction effects might be at a maximum. It is found that the typical efficiency of solar wind energy injection into the magnetosphere is 1.0 x 10^{-3} to 4.0 x 10^{-3}, 100 to 30 times less efficient than during periods of intense southward IMFs. Other energy sinks not included in these numbers are discussed. Estimates of their magnitudes are provided.

Introduction

It has recently been suggested [*Tsurutani et al.*, 1992a] that the efficiency of solar wind energy input into the Earth's magnetosphere via viscous interaction [*Axford and Hines, 1961*] is quite low, -1.2 x 10^{-3}. The interval used for illustration was an intense northward IMF event within the famous August 1972 high speed solar wind stream. The coupling efficiency during this interval was almost two orders of magnitude below that during magnetic reconnection intervals such as those causing intense substorms and storms. If this result is true in general, then it can be concluded that viscous interaction processes (such as the Kelvin-Helmholtz instability on the flanks of the magnetopause/magnetotail: [*Tamao*, 1965; *Chen and Hasegawa*, 1979; *Southwood*, 1974]) may not be of primary importance for direct solar wind energy injection into the magnetosphere. Delayed energy injection (after storage in the magnetotail) may be possible, but from the 1972 event results, it appears that it would have to be delayed by at least five hours or more.

Although the above example shows that this one high speed solar wind stream led to geomagnetic quiet during part of the complex interplanetary event, the study has the inherent difficulty that the interplanetary spacecraft (Pioneer 10) was at a large distance from Earth (2.2 AU) and at a slightly different solar longitude, requiring calculations of radial and coronation delays to match the spacecraft and Earth event times. Because it is difficult to make general conclusions from this single case, further analyses are needed.

The purpose of this paper is to study eleven more examples. We use (ISEE-3) intervals where the IMP had very large

northward components (>10 nT) for long durations (> 3 hours) of time. The events have been previous] y listed in part by Gonzalez *and Tsurutani [1987],* for other purposes. These interplanetary events were taken from 1978-1979, when a complete and continuous ISEE-3 interplanetary plasma and field data set existed.

Results

Figure 1 is an example of a B_N event where B_N is greater than 10 nT for over three hours. From top to bottom are the proton temperature, solar wind velocity, density, BY and B_z (in GSE coordinates), B magnitude and ground based AE and D_{ST} indices. The intense B_N event occurs at 15-21 UT November 11, 1979. The peak B_N value of 20 nT occurs at 18 UT, coincident with the peak B magnitude of -23 nT. Note the exceptionally low AE values and a slightly positive D_{ST} index during the event.

The B_N event is associated with a moderate speed solar wind stream. An interplanetary fast forward shock occurs at -0130 UT November 11. This is indicated by the abrupt increase in proton temperature, solar wind velocity and density and magnetic field magnitude at this time.

'l'able 1 gives the solar wind, magnetospheric and ionospheric parameters for the 11 B_N events. The columns from the left are: 1) the date and time (the listed time is the midpoint of the B_N event), 2) the peak B_N intensity in nT, 3) the duration of the B_N event, 4) the peak magnetic field magnitude, 5) the average AE of the event, and 6) the average D_{ST} during the event. In the latter column, R stands for storm recovery phase and Q is a quiet day. Column 7) is the solar wind velocity, 8) the proton density in nucleons/cm^3, 9) the helium density, and 10) the B_y component in GSE coordinates. When there are two values of BY given, BY was variable during the event, and the two most representative values arc listed. These intense B_N events were often associated with CME-related high speed streams, similar to the previously reported August 1972 event [*Tsurutani et* al., 1992a]. These events were located in either the sheath region behind the shock or in the driver gas proper. A more detailed discussion can be found in *Tsurutani et al. [1988;* 1992 b].

From the above measurements, we will calculate the solar wind energy flux incident upon the magnetosphere, the amount of energy deposited in the magnetosphere/ionosphere at typical auroral and lower latitudes, and finally the efficiency of energy injection. Wc will lead the reader through these straightforward steps.

First, we assume pressure balance at the magnetopause [*Spreiter et al.,* 1966]:

$$k\rho V_{sw}^2 \cos^2\theta = \frac{(fB)^2}{8\pi} \qquad (1)$$

where the ram pressure (Ieft-side of equation) is balanced by the magnetic pressure (right-side). In this expression, p is the total proton plus helium mass density, V_{SW} the solar wind velocity, θ the angle that V_{SW} makes relative to the magnetopause normal, and B the magnetopause magnetic field. The value k *represents* the degree of specular reflection (2.0 is maximum for an elastic collision) and f the magnetic field intensification factor due to the Chapman-Ferraro current. It has been empirically shown that f^2/k -1.69 [*Holzer and Slavin, 1978]* a number wc will use in our estimations.

In Table 2, wc have used the measured values of Table 1 to calculate the value $(p_p + \rho_{He})\ Vsw^2$ (column 1). Tire magnetopause field strength (at the nose) necessary to balance the solar wind ram pressure is calculated using equation 1 (column 2), and the magnetopause stand-off distance in Earth-radii determined by assuming that the magnetopause field strength at its nose is twice the uncompressed dipolar strength (column 3).

Sibeck et al. [1991] found that the field expansion factor of the dawn meridian magnetopause distance relative to the subsolar distance for large B_N values is -1.1. This factor was determined empirically for northward IMF B values between + 4 and + 6 nT. We have used this factor in calculating the cross-sectional area (column 4) of the magnetosphere (a conservative estimate).

Column 5 is the incident solar wind energy flux in erg $cm^{-2}s^{-1}$ and column 6 is the total energy impinging on the dayside magnetosphere, i.e., the values in column 4 times those in column 5.

A commonly used expression for the energy dissipation within the magnetosphere [*Akasofu,* 1981] as applied to typical aurora] and lower latitudes, is:

$$U_T = U_O + U_A + U_J \qquad (2)$$

where U. and U_A are the ring current and auroral energies, and U_J the rate of Joule heating The Joule heating rate has been approximated by $2 \times 10^5 AE(nT)$ ergs s^{-1} and the aurora] particle energy by 1 x 1015 AE (nT) ergs s^{-1} [*Akasofu,* 1981]. The value U. is given by $4 \times 10^{20}(dD_{ST}/dt + D_{ST}/\tau)$ erg S-l with D_{ST} given in nT. Here τ is -10 hrs, the average ring current decay time. Baumjohann and Kamide [)984] have shown that Joule heating is linearly proportional to AE throughout the range of AE 200 nT to 1000 rrT, the specific range of interest here.

From Table 1, it is noted that there is no discernible ring current energy injection for any of these events. Thus, we take U. -O for these cases. $U_A + U_J$ can bc approximated as equal to 3×10^{15} AE (nT) erg s^{-1}. U_T has been calculated using the ahove relationships for each of the 11 events and is given as column 1 of Table 3. The energy deposition in the magnetosphere relative to the total solar wind energy flux impinging upon the magnetosphere, e.g., the efficiency of energy transfer, is given in column 2. The latter values arc relatively constant. For 9 of 11 events, the efficiency varies from 1.0×10^{-3} to 4.0×10^{-3}. Onc event had an energy efficiency that was anomalously low, 7.1×10^{-4} on 29-30 May 1979. Another event had an efficiency that was anomalously high. This is on October 7, 1980 with an apparent efficiency of 1.1×10^{-2}.

The IMF By value is listed in the last column of Table 1. On the supposition that magnetic reconnection could still take place if BY is large (during B_N events), we compared the solar wind energy input efficiency to that of the sign and magnitude of the IMF BY. No obvious correlations arc apparent.

The above expression in (2) dots not include energy deposition at high (polar cap) latitudes, however. It is well known that the aurora] oval shrinks during, B_N events and it is possible that some energy deposition occurs poleward of the AE stations (>68° MLAT). *Makita et al.* [1988], following the work of *Meng [198* 1], have examined polar particle precipitation during strong interplanetary BN intervals. They find that the entire polar region is often filled with "burst-type soft electron precipitations". From the Figurcs of Makita et rd., [1988], wc find a flux between 10^{-2} to 10 erg $cm^{-2}s^{-1}ster^{-1}$. Integrating from 68" to 85° magnetic

latitude, we determine a polar cap size of 3.S x 10^{17} cm^2. Thus, the energy flux is -4.4 x 10^{16} to 4.4 x 10^{17} erg S-l over the two polar caps. Although the lower energy flux limit is negligible in comparison to the numbers *in* Table 2, we note that the upper energy limit is comparable to the aurora] zone plus ring current energy fluxes derived from the *Akasofu [1981]* expression. Thus, there should be an uncertainty factor of -2 associated with our solar wind-magnetosphere coupling efficiencies, due to polar cap precipitation.

High latitude Joule heating is another magnetospheric/ionosphere energy sink that could be missed by the energy expression, equation (2). There are indications that there can be significant high latitude polar cap potentials during intense interplanetary B_N intervals [*Heelis and Coley,* 1992; Freeman *et al.,* 1993]. However, 7. *Fuller-Rowell* [personal communication, 1994] has indicated that the ratio of the energy associated with Joule heating to that of particle precipitation will be no more than a factor of 2-3 for the polar cap during large IMF B_N events, a factor of -2 being a typical number.

Discussion

In this work we have examined eleven intense, long-duration (>3 hours) B_N events to estimate the solar wind coupling efficiency to the magnetosphere. For most of the 11 events, we find relatively constant values, only varying by a factor of 3. No obvious solar wind features arc present which account for this slight variability, if it is real. It should be noted that the numbers (and efficiencies) given in Table 3 maybe low by a factor of 4 if the polar cap precipitation reaches a level of 10^{1} ergs cm-z $s^{-1}ster^{-1}$ and Joule heating is twice this value. However, since this precipitation level and Joule heating rate are only upper limits, the values in Table 3 should give reasonable estimates.

The initial idea of a viscous-like interaction between the solar wind (magnetosheath) and the magnetosphere/magnetotail was first presented by *Axford and Hines [1961].* Since that time several attempts have been made to determine the specific mechanism of interaction and to try to bound the limits of its energy efficiency. *Sonnerup [1980]* considered a purely viscous model which had no current limitation effects. He determined a potential drop across the boundary layers to be only 10-15% of the total potential drop across the magnetosphere. *Eastman and Hones [1970]* and *Sckopke* et al. [1981] experimentally arrived al 5-25 kV potentials across the boundary layers (see review by *Cowley* [1982]), a small fraction of the total cross-magnetospheric potential drop, in agreement with Sonnerup's model. *Mozer [)984],* from 28 magnetopause crossings near local dusk, determined the dusk-to-dawn potential drops were only a fcw kV and concluded that this potential was less than 10% of the total magnetospheric electric potential. *Baumjohann and Haerendel [1986]* demonstrated that viscous interaction plays only a "minor role" for equatorial convection at L = 6.6. However, more recently, [*Freeman et al., 1993]* have calculated a 60-80 kV potential drop across the polar cap during an intense northward IMF event.

Even though the potential drops across the boundary layers appear to be somewhat bounded (most estimates give small potential drops), it is still difficult to derive an energy flux because of the lack of a quantitative knowledge of the current systems in these regions. If we make a very simplistic assumption that viscous interaction is - 10% as efficient as

magnetic reconnection and 10% of the solar wind energy flux gets into the magnetosphere during magnetic storms, this implies that viscous interaction could provide 1% of the solar wind energy to the magnetosphere/magnetotail. The numbers presented in this paper are lower than this value, and hence arc consistent with this overall picture.

Another type of solar wind energy transfer mechanism suggested by *Sonnerup* [1980] is cross-field diffusion by resonant wave-particle interactions at the dayside magnetopause [*Tsurutani and Thorne, 1982; Gendrin, 1983]*. The ultimate energy source for the broadband ELF/VLF waves must be the solar wind/magnetosphere interaction. It has been suggested that these wave-particle interactions are responsible for the dayside aurora [*Tsurutani et al., 1981; Thorne and Tsurutani, 1991]. The* latter has an intensity of -1.0 erg $cm^{-2} s^{-1}$ [*Eather,* private comm., 1981]. Assuming a latitudinal width of -1.0 degree (100 km) for the precipitation region and a precipitation latitude of 6S°, one derives an energy deposition rate of $\sim 10^{16}$ ergs s^{-1} over the two auroral zones. This number represents about 0.01% of the solar wind ram energy flux, or only 1070 of the energy dissipated in the magnetosphere during intense B_N events.

The above numbers give an estimate of the energy injection efficiency during intense IMF B_N events. It should be noted that magnetic reconnection in the cusp regions and associated, localized, polar cap potential drops are possible [*Reiff et* al., 1981], so these numbers are thus only an upper limit to the efficiency of viscous interaction (and also of reconnection). We have seen that the sum of UT, polar cap precipitation and Joule heating are equal to or less than 1% of the solar wind energy flux. It will be quite useful to know how much energy is lost down the tail [see *Owen and Slavin,* 1992] and how much Joule heating occurs over the polar cap to refine this estimate further. For the latter problem, we will examine the TIROS date in the near future.

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B. T. Tsurutani, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109. (e-mail: btsurutani@jplsp.jpl. nasa.gov)

W. D. Gonzalez., Instituto de Pesquisas Espaciais, Sao Paulo, Brazil. (e-mail: gonzalez@das.inpe.br)

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Figure 1. An example of a B_N event, from 15-21 UT, November 11, 1979. B_N is $\geq$ 10 nT, and reaches a peak value of 20 nT at 18 UT. By is large and variable during the interval. This event is associated with a moderate speed solar wind stream. No driver gas is evident.

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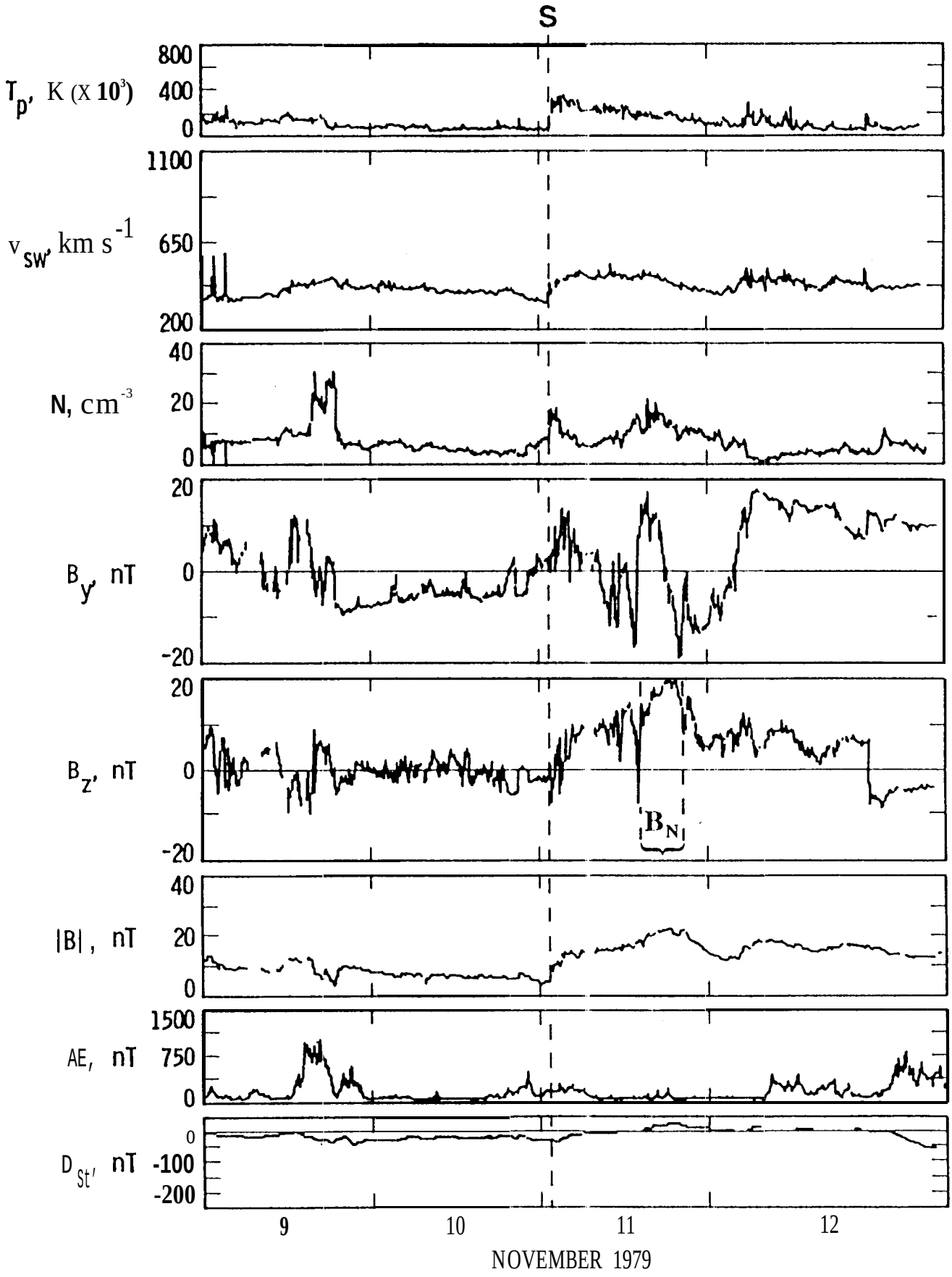
S
800
400
0
T_p, K (X 10^3)
1100
650
200
v_{SW}, km s^{-1}
40
20
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N, cm^{-3}
20
0
-20
B_y, nT
20
0
-20
B_z, nT
B_N
40
20
0
|B|, nT
1500
750
0
AE, nT
0
-100
-200
D_{St}, nT
9
10
11
12
NOVEMBER 1979

Table I. Interplanetary and Magnetospheric Parameters for the B_N Events

Date (U.T.)	Peak B_N (nT)	Duration (h)	Peak |B| (nT)	AE (nT)	D_{ST} (nT)	v (km s^{-1})	ρ_p (n cm^{-3})	ρ_{He} (n cm^{-3})	B_y (nT)
1. 1X December 1978 (0100)	15	3	26	175	0	450	10.0	0.8	-12,*14
2. 2 I February 1979(1 200)	20	A	22	75	R	560	12.0	().4	+22
3 3 April (1230)	[2	3	14	75	R	440	8.0	().4	-4
4. 5 April (0300)	20	4	33	200	R	605	11.0	1.0	-10,+20
5 5 Aprill (1230)	30	4	40	3(YJ	()	695	15.0	1.1	-8,+18
6. 29-30 May (21 30)	15	3	23	150	0+	750	20.0	1.0	+8
7. 20 August (0830)	18	6	30	150	0+	670	13.0	().4	25, +5
8. 18-19 September (2400)	12	3	15	35	R(Q)	365	12.0	0.8	+6.5
9. 6 October (1800)	Ix	3	20	I 10	R	370	45.0	2.0	+10,-10
I 0. 7 October (0800)	16	4	20	350	R	425	I 2.0	0.2	+4
11. I 1 November (1800)	20	6	23	100	0+	450	12.0	0.8	+12,-10

Table 2. Calculated Interplanetary and Magnetospheric Parameters

	$(\rho_{ff} + \rho_{ffe}) V_{sw}^2$ (gm cm^{-1} s^{-2})	B_{mp} (Gauss)	R_{so} (R_E: 6380 km)	Area (cm^2)	1/2MN V_{SW}^3 (erg cm^{-2} s^{-1})	E_T (ergs-l)
1.	4.5X 10^{-8}	x.2 x10^{-4}	9.0	1.3 x 10^{20}	1.0	1.3 x 10^{20}
2.	7.1 x 10^{-8}	1.0 x 10^{-3}	8.4	1.1 x 10^{20}	2.0	2.2 x 10^{20}
7	3.1 x 10^{-8}	6.8 x 10^{-4}	9.6	1.4 x 10^{20}	0.7	1.0 x 10^{20}
4.	9.2 x10^{-8}	1.2 x10^{-3}	7.9	7.0 x 10^{19}	2.8	2.0 x 10^{20}
5.	1.6 x JO-7	1.5 X10-7	7.3	8.2 x 10^{19}	5.4	4.4 x 10^{20}
6.	2.7 x 10-7	1.X x10^{-3}	6.9	7.4 x 10^{19}	8.5	6.? x 10^{20}
7.	1.1 x 10^{-7}	1.3 x10^{-3}	7.7	9.2 x10^{19}	3.7	1.3 x 10^{20}
8.	3.4 x 10^{-8}	7.1 x 10^{-4}	9.5	1.4 x 10^{20}	0.6	8.4 x 10^{19}
9.	1.2 x 10^{-7}	1.3 x10^{-3}	7.7	9.2 x10^{19}	2.2	2.0 x 10^{20}
10.	3.9 x 10^{-8}	7.6 x 10^{-4}	9.2	1.3 x 10^{20}	0.8	1.0 x 10^{20}
11.	5.1 x 10^{-8}	8.7 x 10^{-4}	8.8	1.2 x 10^{20}	1.2	1.4 x 10^{20}

Table 3. U_T and Energy Transfer Efficiency

	dE_{mag}/dt $erg\ s^{-1}$	η efficiency
1.	5.3×10^{17}	4.0×10^{-3}
2.	2.2×10^{17}	1.0×10^{-3}
3.	2.2×10^{17}	2.2×10^{-3}
4.	6.0×10^{17}	3.0×10^{-3}
5.	9.0×10^{17}	2.0×10^{-3}
6.	4.5×10^{17}	7.1×10^{-4}
7.	4.5×10^{17}	3.4×10^{-3}
8.	1.1×10^{17}	1.3×10^{-3}
9.	3.3×10^{17}	1.7×10^{-3}
10.	1.1×10^{18}	1.1×10^{-2}
11.	3.0×10^{17}	2.1×10^{-3}